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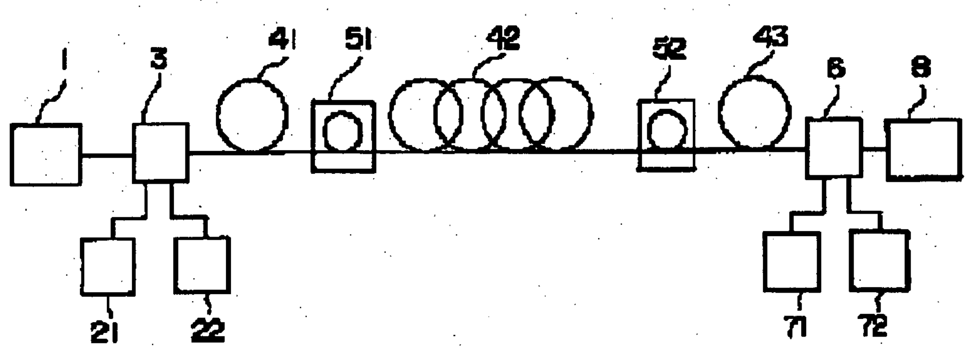
## (54) OPTICAL FIBER COMMUNICATION SYSTEM

(57) Abstract:

PROBLEM TO BE SOLVED: To furthermore extend the span length of a very long span communication system for sending excitation light from both transmitting and receiving ends to an optical fiber amplifier on an optical fiber transmission line.

SOLUTION: Since an output from an exciting semiconductor laser has an upper limit, 2nd excitation light shorter than the wavelength of 1st excitation light by the Ramon shift distance of an optical fiber transmission line 41 to 43 is inputted from both the transmitting and receiving ends together with the 1st excitation light. The 2nd excitation light is shifted to the 1st wavelength by a Raman scattering effect during the transmission of the transmission line 41 to 43 and the power of the 1st excitation light is increased, so that the span length can be furthermore extended.



# ULTRA WIDE-BAND RAMAN AMPLIFICATION WITH A TOTAL GAIN-BANDWIDTH OF 132 nm OF TWO GAIN-BANDS AROUND 1.5 μm

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*Abstract: The largest transparent gain-bandwidth of 132 nm around 1.5 μm for a 50 km transmission fiber is achieved using a novel Raman amplifier. The amplifier has a distributed amplification section and a two-gain-band discrete amplification section.*

## Introduction

The fiber Raman amplifier (RA) can provide a gain-band at arbitrary wavelength region in the low-loss silica fiber window (ex. 1.3 - 1.7 μm), if the corresponding high-power pump light source is available /1-6/. We can increase the transmission capacity of wavelength-division-multiplexing (WDM) systems using the multiple gain-bands of such RAs as well as rare-earth doped fiber amplifiers in the parallel configuration /7, 8/.

Several single-wavelength pumped RAs were reported to operate around 1.5 μm (1.4 - 1.7 μm) with a gain-bandwidth of about 10 - 40 nm /1-6/. On the other hand, multi-wavelength pumped RAs provided wide gain-bandwidths of up to about 100 nm /3, 9-11/. The latter bandwidths are limited by the fundamental bandwidth of about 100 nm around 1.5 μm (about 13 THz) of silica-based RAs.

This study reports a novel two-gain-band RA with a total transparent gain-bandwidth of 132 nm around 1.5 μm for a 50-km long transmission fiber. The proposed RA had a distributed amplification section and a two-gain-band discrete amplification section in a novel configuration. The RA was used as an in-line amplifier in a transmission experiment so that error-free operation was successfully confirmed.

## Experiment

The amplifier configuration is shown in Figure 1. The amplifier had a distributed RA and a discrete RA in serial configuration. The distributed RA had a 50 km dispersion-shifted fiber (DSF) as a gain medium, which was backward pumped by a 1415 nm Raman pump light source (P-1). The discrete RA had two gain-units, a devider, and a combiner. The devider and combiner were dielectric multi-layer filters with the boundary wavelength region of 1530 - 1540 nm.

The short wavelength gain-unit had a 5.0-km Raman fiber (germanium co-doped high-numerical-aperture silica fiber), a 1419-nm pump light source (P-2), and a gain-equalizer. The gain-equalizer was a cascade of a Mach-Zehnder filter and a notch filter, and had a peak loss of 13 dB at 1510 nm.

The long wavelength gain-unit had three Raman fibers (8.3, 5.0, and 5.0 km) and four pump light source (P-3, -4, -5, and -6). The three Raman fibers were optically separated by an intermediate circulator and an isolator. P-1 and -2 were the cascaded fiber Raman lasers /1-4/. P-3 and -5 were the laser diode modules /11/, and P-4 and -6 were the amplified spontaneous light sources /6/. P-5 had three pump wavelengths of 1465, 1495, and 1510 nm, and P-3, -4, and -6 had wavelengths of 1475, 1545, and 1545 nm, respectively. Pump powers launched into the fibers were 407, 295, 204, 229, 471, and 240 mW, for P-1, ~ P-6, respectively.

The three stage amplification configuration for the long wavelength gain-unit was employed so that wide gain-bandwidth and low noise figure were obtained while suppressing the intensity noise due to the double Rayleigh scattering /1/. The positions of the four pump light sources for the long wavelength unit were optimised for low noise figure and high pump efficiency. On the other hand, the two-stage distributed/discrete amplification configuration for the short wavelength gain-band was employed so that high optical signal-to-noise ratio (SNR) was achieved while suppressing the intensity noise.

Figure 2 shows measured gain spectra. The distributed and discrete gains are shown in Figure 2(a), the gross gain and DSF loss are shown in Figure 2(b), and the net gain is shown in Figure 2(c). The net gain equals to the gross gain minus the DSF loss. The bandwidths with a positive net

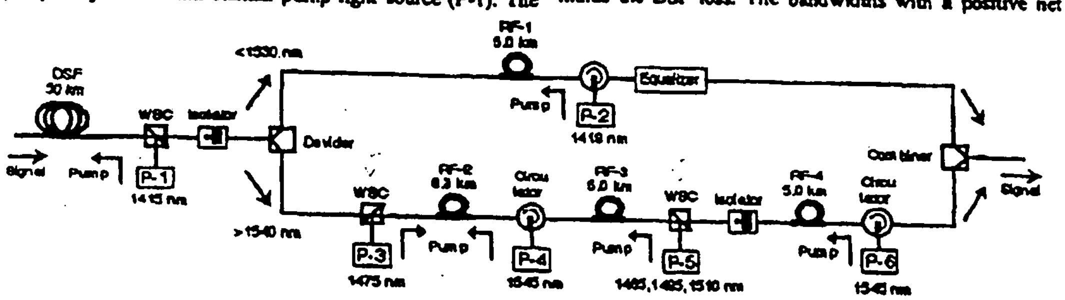


Fig. 1 Amplifier configuration. RF: Raman fiber, P: pump module, WSC: wavelength selective coupler.

gain were 41 nm (1486.5 - 1527.5 nm) and 91 nm (1569.5 - 1660.5 nm) for the short and long wavelength gain-bands, respectively. The large residual gain excursion in the short gain-band can be significantly reduced by employing multi-wavelength pumping.

The noise figure spectrum of the discrete RA is shown in Figure 3(a). The average noise figure values were 8.0 and 10.3 dB for the short and long wavelength bands, respectively. The values contained the loss of the optical components of 3.0 dB at the input point of the discrete RA, which can be reduced to about 1.5 dB using an integrated optical component instead of the optical components.

The optical SNR spectra measured for the proposed RA are shown in Figure 3(b). Calculated optical SNR spectra for the same transmission line using a discrete optical amplifier with a noise figure of 3, 6, or 9 dB are also shown. The input signal power and noise bandwidth were -10 dBm and 0.1 nm, respectively. Owing to the distributed gain, SNR improvement was achieved in the wavelength region of shorter than 1600 nm. The improvement increased with the distributed Raman gain. The optical SNR for the proposed RA was larger than that for the discrete amplifier with a 9.5-dB noise figure in the 132-nm transparent gain-bandwidth.

The proposed RA was used as an in-line amplifier in our transmission experiment. The case of single channel signal light was tested for simplicity instead of multiple WDM signal lights. The signal light was modulated by a $LiNbO_3$ modulator at 2.5 Gbit/s with an NRZ PRBS format. The optical receiver had an optical bandpass filter with a bandwidth of less than 1 nm, and a *p-i-n* photodiode receiver circuit. The input signal light power was set at -10 dBm. The error-free operation with bit-error rates (BERs) of less than $10^{-10}$ was confirmed for all signal wavelengths tested. Figure 4 shows the measured receiver sensitivity spectra at BER = $10^{-9}$. Power penalties between the back-to-back and after transmission were less than 1.2 dB. Therefore, the intensity noise due to the double Rayleigh scattering was effectively suppressed with the multi-stage amplification configuration.

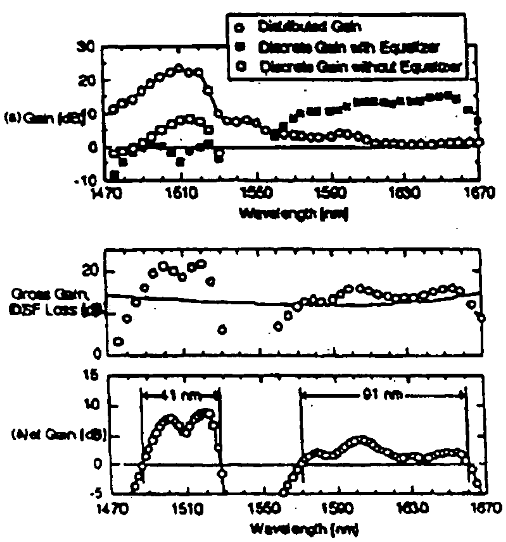


Fig. 2 Gain spectra.
(a) Distributed and discrete gains.
(b) Amplifier gross gain and DSF loss.
(c) Amplifier net gain.

## Conclusion

The largest transparent gain-bandwidth of 132 nm around 1.5 µm for a 50 km long DSF was achieved using a novel two-gain-band Raman amplifier. The proposed amplifier had a distributed amplification section and a two-gain-band discrete amplification section. The amplifier offered optical SNRs higher than the discrete optical amplifier with a noise figure of 9.5 dB. The amplifier was tested as an in-line amplifier in a transmission experiment so that error-free operation was successfully confirmed.

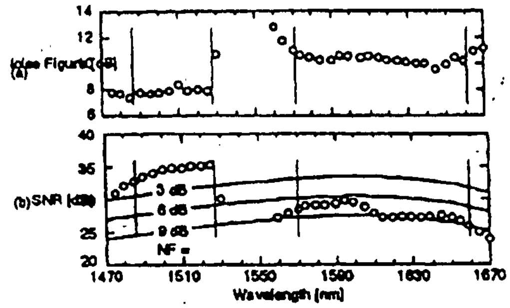


Fig. 3 Optical noise figure and SNR spectra.
(a) Noise figure for the discrete amplifier.
(b) SNR for the over all distributed/discrete amplifier.
O: measred, —: caluculated.

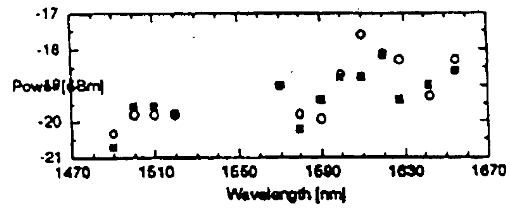


Fig. 4 Received signal power spectra.
O: back-to-back, ▲: with amplifier.


## Acknowledgement

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